
Lepton flavor violation in the SUSY seesaw model: an update

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We present an update of previous work on charged lepton flavor violation (LFV) in the seesaw model. The most recent neutrino data fits and post WMAP mSUGRA benchmark scenarios are used as input. In this framework we compare the sensitivity of rare radiative decays on the right-handed Majorana mass scale M_R with the reach in slepton-pair production at a future linear collider.

1 Introduction

The evidence for flavor violating neutrino oscillations provides strong motivation to search for LFV also in the charged lepton sector. While charged lepton-flavor violating processes are suppressed in the Standard Model with right-handed neutrinos [1] due to the light neutrino masses, in supersymmetric models new sources of lepton flavor violation exist. For example, the massive neutrinos affect the renormalization group equations of the slepton masses and the trilinear couplings, and give rise to non-diagonal matrix elements inducing LFV [2]. This finding has initiated a prospering research activity both on LFV in rare decays [3, 4, 5] as well as on lepton-flavor violating processes at future colliders [6]. Recently, we performed a comparative study of the sensitivity of rare radiative decays on the right-handed Majorana mass scale M_R [7] and the reach in slepton-pair production at a future linear collider [8] in the context of the SUSY seesaw model. We used mSUGRA benchmark scenarios [12] designed for linear collider studies and paid particular attention to the uncertainties in the neutrino input parameters. Here we present an update of these works, implementing the most recent neutrino data fits and refined post WMAP mSUGRA benchmark scenarios.

2 Neutrino parameters

In the last decade a rather unique picture of neutrino mixing has emerged. As can be seen in Fig. 1, large to maximal mixing has been established for solar and atmospheric neutrinos, while the third angle is strongly constrained by reactor measurements. Recently, this picture of neutrino mixing has been refined further. The results of the KamLAND reactor experiment confirmed the disappearance of solar electron neutrinos, while the SNO experiment allowed for the first time to study both solar neutrino appearance and disappearance via the separate measurement of charged current, elastic scattering and neutral current interactions. Moreover, the first data of the K2K long baseline accelerator experiment indicate a confirmation of atmospheric neutrino oscillations. At the time when a linear collider will be in operation, even more precise measurements of the neutrino parameters will be available than today. In order to simulate the expected improvement, we take the central values of the mass squared differences $\Delta m_{ij}^2 = |m_i^2 - m_j^2|$ and mixing angles θ_{ij} from the most recent global fit to existing data [10] with errors that indicate the anticipated 2σ intervals of running and proposed experiments as further explained in [7]:

$$\tan^2 \theta_{23} = 1.10_{-0.60}^{+1.39}, \quad \tan^2 \theta_{13} = 0.006_{-0.006}^{+0.001}, \quad \tan^2 \theta_{12} = 0.43_{-0.22}^{+0.47}, \quad (1)$$

$$\Delta m_{12}^2 = 6.9_{-0.36}^{+0.36} \cdot 10^{-5} \text{ eV}^2, \quad \Delta m_{13}^2 = 2.6_{-1.2}^{+1.2} \cdot 10^{-3} \text{ eV}^2. \quad (2)$$

Furthermore, for the lightest neutrino mass we assume $m_1 \leq 0.03 \text{ eV}$, where $m_1 \simeq 0 \text{ eV}$ corresponds to the case of a hierarchical spectrum, while $m_1 \simeq 0.03 \text{ eV}$ approaches the degenerate case.

3 mSUGRA benchmark scenarios

For our numerical investigations we focus on the mSUGRA benchmark scenarios proposed in [11] for linear collider studies. These models are consistent with direct SUSY searches, Higgs searches, $b \rightarrow s\gamma$, and astrophysical constraints. Recently, the precision measurement of the cosmic microwave background by the WMAP experiment combined with previously available data provided a refined estimate of the density of cold dark matter in the universe. Assuming that most of the dark matter is composed of neutralino LSPs, the smaller neutralino relic density led to a shift of previous benchmark points [12] towards lower values of the universal scalar mass m_0 . In table 1 we specify the mSUGRA parameters of the benchmark scenarios B', C', G', and I'. These are the only models of [11] with left-handed sleptons which are light enough to be pair-produced at e^+e^- colliders with c.m. energies $\sqrt{s} = 500 \div 800 \text{ GeV}$.

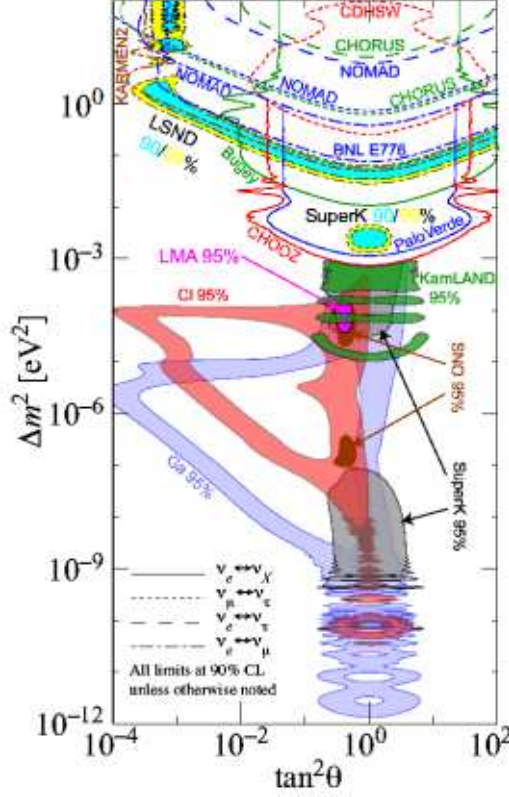


Fig. 1. Summary of evidences for neutrino oscillations [9].

Scenario	$m_{1/2}/\text{GeV}$	m_0/GeV	$\tan\beta$	\tilde{m}_6/GeV	$m_{\tilde{\chi}_1^0}/\text{GeV}$
B'	250	60	10	192	98
C'	400	85	10	291	163
G'	375	115	20	291	153
I'	350	175	35	310	143

Table 1. Parameters of selected mSUGRA post WMAP benchmark scenarios [11]. The sign of μ is chosen to be positive and A_0 is set to zero. Given are also the masses of the heaviest charged slepton and the lightest neutralino, that is the LSP.

4 SUSY seesaw mechanism and slepton mass matrix

If three right-handed neutrino singlet fields ν_R are added to the MSSM particle content, one gets the following additional terms in the superpotential [4]:

$$W_\nu = -\frac{1}{2}\nu_R^{cT} M \nu_R^c + \nu_R^{cT} Y_\nu L \cdot H_2. \quad (3)$$

Here, Y_ν is the matrix of neutrino Yukawa couplings, M is the right-handed neutrino Majorana mass matrix, and L and H_2 denote the left-handed lepton and hypercharge $+1/2$ Higgs doublets, respectively. At energies much below the mass scale of the right-handed neutrinos, W_ν leads to the mass matrix

$$M_\nu = m_D^T M^{-1} m_D = Y_\nu^T M^{-1} Y_\nu (v \sin \beta)^2, \quad (4)$$

for the left-handed neutrinos. Thus, light neutrino masses are naturally obtained if the typical scale of the Majorana mass matrix M is much larger than the scale of the Dirac mass matrix $m_D = Y_\nu \langle H_2^0 \rangle$, where $\langle H_2^0 \rangle = v \sin \beta$ is the appropriate Higgs v.e.v. with $v = 174$ GeV and $\tan \beta = \frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle}$. Diagonalization of M_ν by the unitary MNS matrix

$$U = \text{diag}(e^{i\phi_1}, e^{i\phi_2}, 1) V(\theta_{12}, \theta_{13}, \theta_{23}, \delta), \quad (5)$$

where $\phi_{1,2}$ and δ are the Majorana and Dirac phases, respectively, and θ_{ij} are the mixing angles, leads to the light neutrino mass eigenvalues m_i :

$$U^T M_\nu U = \text{diag}(m_1, m_2, m_3). \quad (6)$$

The other neutrino mass eigenstates are too heavy to be observed directly. However, they give rise to virtual corrections to the slepton mass matrices that can be responsible for observable lepton-flavor violating effects. In particular, the 6×6 mass matrix of the charged sleptons is given by

$$m_l^2 = \begin{pmatrix} m_{l_L}^2 & (m_{l_{LR}}^2)^\dagger \\ m_{l_{LR}}^2 & m_{l_R}^2 \end{pmatrix} \quad (7)$$

with

$$(m_{l_L}^2)_{ab} = (m_L^2)_{ab} + \delta_{ab} \left(m_{l_a}^2 + m_Z^2 \cos 2\beta \left(-\frac{1}{2} + \sin^2 \theta_W \right) \right) \quad (8)$$

$$(m_{l_R}^2)_{ab} = (m_R^2)_{ab} + \delta_{ab} (m_{l_a}^2 - m_Z^2 \cos 2\beta \sin^2 \theta_W) \quad (9)$$

$$(m_{l_{LR}}^2)_{ab} = A_{ab} v \cos \beta - \delta_{ab} m_{l_a} \mu \tan \beta. \quad (10)$$

When m_l^2 is renormalized from the GUT scale M_X to the electroweak scale one obtains, in mSUGRA,

$$m_L^2 = m_0^2 \mathbf{1} + (\delta m_L^2)_{\text{MSSM}} + \delta m_L^2 \quad (11)$$

$$m_R^2 = m_0^2 \mathbf{1} + (\delta m_R^2)_{\text{MSSM}} + \delta m_R^2 \quad (12)$$

$$A = A_0 Y_l + \delta A_{\text{MSSM}} + \delta A, \quad (13)$$

where m_0 is the common soft SUSY-breaking scalar mass and A_0 the common trilinear coupling. The terms $(\delta m_{L,R}^2)_{\text{MSSM}}$ and δA_{MSSM} are well-known flavor-diagonal corrections. In addition, the evolution generates off-diagonal terms in $\delta m_{L,R}^2$ and δA^2 which in leading-log approximation are given by [5]

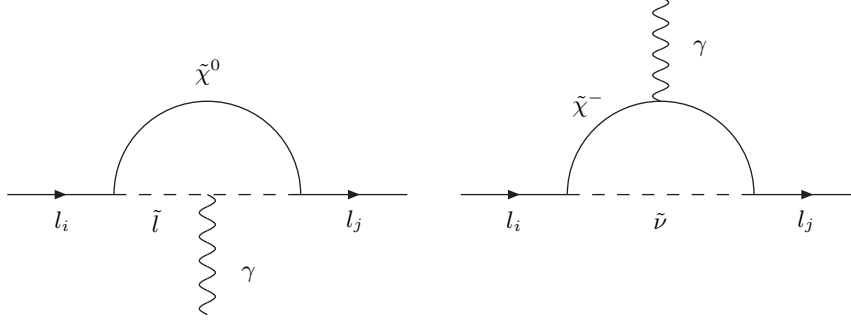


Fig. 2. Diagrams for $l_i^- \rightarrow l_j^- \gamma$ in the MSSM

$$\delta m_L^2 = -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger L Y_\nu) \quad (14)$$

$$\delta m_R^2 = 0 \quad (15)$$

$$\delta A = -\frac{3A_0}{16\pi^2}(Y_l Y_\nu^\dagger L Y_\nu) \quad (16)$$

with

$$L_{ij} = \ln \left(\frac{M_X}{M_i} \right) \delta_{ij}, \quad (17)$$

and M_i , $i = 1, 2, 3$ being the eigenvalues of the Majorana mass matrix M . In the above, we have chosen a basis in which the charged lepton Yukawa couplings and M are diagonal.

The product of the neutrino Yukawa couplings $Y_\nu^\dagger L Y_\nu$ entering these corrections can be determined as follows [4]. By inverting (6), one obtains

$$Y_\nu = \frac{1}{v \sin \beta} \text{diag} \left(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3} \right) R \text{diag} \left(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3} \right) U^\dagger, \quad (18)$$

where R is an unknown complex orthogonal matrix. For real R and degenerate right-handed Majorana masses, R as well as ϕ_1 and ϕ_2 drop out from the product $Y_\nu^\dagger L Y_\nu$. Using then the neutrino data sketched in section 2 as input the result is evolved to the unification scale M_X . In what follows we refer to this illustrative case which suffices for the present discussion. For small neutrino masses, $m_i^2 \ll \Delta m_{ij}^2$, the above procedure yields

$$(Y_\nu^\dagger L Y_\nu)_{ab} \approx \frac{M_R}{v^2 \sin^2 \beta} \left(\sqrt{\Delta m_{12}^2} U_{a2} U_{b2}^* + \sqrt{\Delta m_{23}^2} U_{a3} U_{b3}^* \right) \ln \frac{M_X}{M_R}. \quad (19)$$

Upon diagonalization, the flavor off-diagonal corrections in (11)-(13) generate flavor-violating couplings of the slepton mass eigenstates.

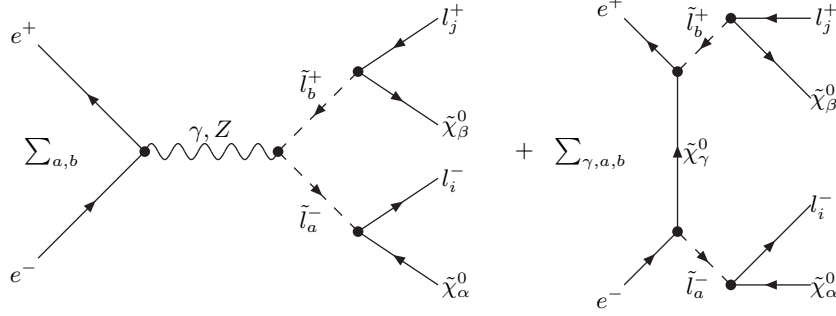


Fig. 3. Diagrams for $e^+e^- \rightarrow \tilde{l}_b^+ \tilde{l}_a^- \rightarrow l_j^+ l_i^- \tilde{\chi}_\alpha^0 \tilde{\chi}_\beta^0$

5 Charged lepton flavor violation

At low energies, the flavor off-diagonal correction (14) induces the radiative decays $l_i \rightarrow l_j \gamma$. From the photon penguin diagrams shown in Fig. 2 with charginos/sneutrinos or neutralinos/charged sleptons in the loop, one derives the decay rates [4, 5]

$$\Gamma(l_i \rightarrow l_j \gamma) \propto \alpha^3 m_{l_i}^5 \frac{|(\delta m_L)_{ij}^2|^2}{\tilde{m}^8} \tan^2 \beta, \quad (20)$$

where \tilde{m} characterizes the sparticle masses in the loop. Because of the dominance of the penguin contributions, the process $\mu \rightarrow 3e$, and also μ - e conversion in nuclei is directly related to $\mu \rightarrow e \gamma$, e.g.,

$$\frac{Br(\mu \rightarrow 3e)}{Br(\mu \rightarrow e \gamma)} \approx \frac{\alpha}{8\pi} \frac{8}{3} \left(\ln \frac{m_\mu^2}{m_e^2} - \frac{11}{4} \right). \quad (21)$$

At high energies, a feasible test of LFV is provided by the process $e^+e^- \rightarrow \tilde{l}_b^+ \tilde{l}_a^- \rightarrow l_j^+ l_i^- \tilde{\chi}_\alpha^0 \tilde{\chi}_\beta^0$. From the Feynman graphs displayed in Fig. 3, one can see that LFV can occur in production and decay vertices. For sufficiently narrow slepton widths $\Gamma_{\tilde{l}}$ and degenerate masses, the cross-section can be approximated by

$$\sigma_{i \neq j}^{\text{pair}} \propto \frac{|(\delta m_L)_{ij}^2|^2}{\tilde{m}^2 \Gamma_{\tilde{l}}^2} \sigma(e^+e^- \rightarrow \tilde{l}_j^+ \tilde{l}_i^-) Br(\tilde{l}_j^+ \rightarrow l_j^+ \tilde{\chi}_0^0) Br(\tilde{l}_i^- \rightarrow l_i^- \tilde{\chi}_0^0). \quad (22)$$

where $\sigma(e^+e^- \rightarrow \tilde{l}_j^+ \tilde{l}_i^-)$ can be replaced by the flavor-diagonal cross-section for slepton pair production. The flavor change is described by the factor in front of the r.h.s. of (22) resulting in a single mass insertion.

In the following numerical study we have not assumed slepton degeneracy and have summed the amplitudes for the complete $2 \rightarrow 4$ processes coherently over the intermediate slepton mass eigenstates.

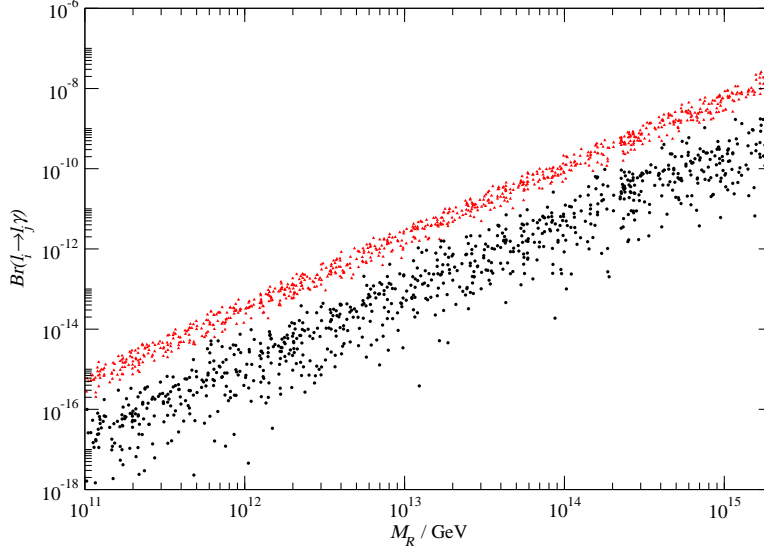


Fig. 4. Branching ratio of $\tau \rightarrow \mu \gamma$ (upper band) and $\mu \rightarrow e \gamma$ (lower band) in the mSUGRA scenario B'.

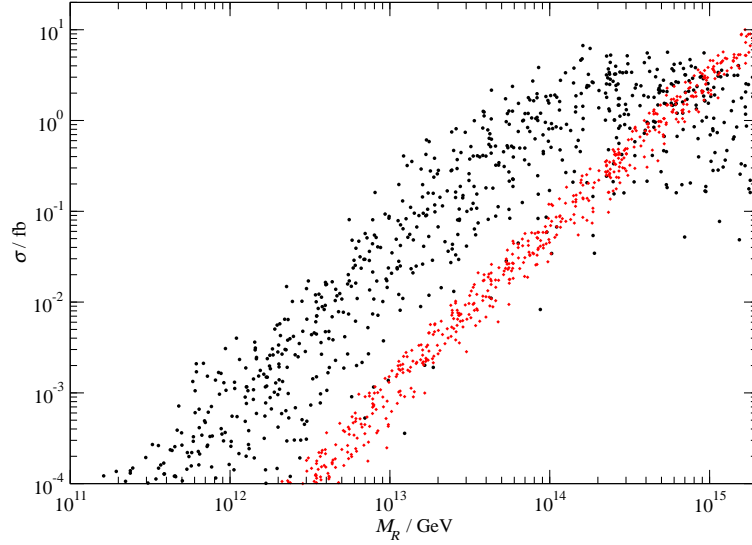


Fig. 5. Cross-sections for $e^+e^- \rightarrow \mu^+e^- + 2\tilde{\chi}_1^0$ (upper band) and $e^+e^- \rightarrow \tau^+\mu^- + 2\tilde{\chi}_1^0$ (lower band) at $\sqrt{s} = 500$ GeV for the mSUGRA scenario B'.

6 Numerical Results

Fig. 4 illustrates the dependence of $Br(\mu \rightarrow e \gamma)$ and $Br(\tau \rightarrow \mu \gamma)$ on the Majorana mass M_R . The spread of the predictions reflects the uncertainties in

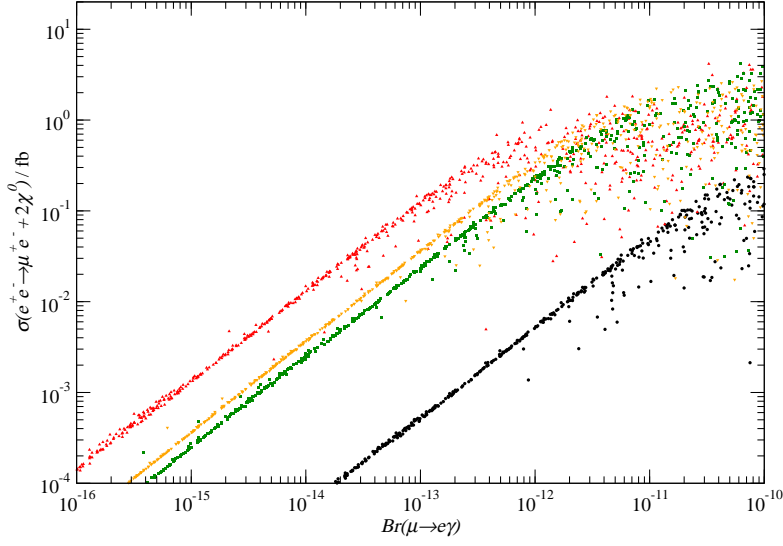


Fig. 6. Correlation between $Br(\mu \rightarrow e\gamma)$ and $\sigma(e^+e^- \rightarrow \mu^+e^- + 2\tilde{\chi}_1^0)$ at $\sqrt{s} = 800$ GeV for the mSUGRA scenarios (from left to right) C', G', B' and I'.

the neutrino data. The update of neutrino and SUSY parameters leads to only a slight decrease of $Br(\mu \rightarrow e\gamma)$ as compared to the previous results published in [7]. One sees that a branching ratio in the range between the present bound and the sensitivity limit of the new PSI experiment, that is $10^{-11} \gtrsim Br(\mu \rightarrow e\gamma) \gtrsim 10^{-13}$, would point at a value of M_R between $5 \cdot 10^{12}$ GeV and $5 \cdot 10^{14}$ GeV. On the other hand, $Br(\tau \rightarrow \mu\gamma)$ is more strongly affected by the smaller value of m_0 in the new benchmark models [11], resulting in a reduction by a factor of about 5 as compared to the results in [7]. Even if $Br(\tau \rightarrow \mu\gamma) = 10^{-8}$ is reached, the goal of SUPERKEKB and LHC [13], one would only probe $M_R \gtrsim 10^{15}$ GeV [7]. Nevertheless it is interesting to note that $\tau \rightarrow \mu\gamma$ is much less affected by the neutrino uncertainties than $\mu \rightarrow e\gamma$.

Analogously, Fig. 5 shows the M_R dependence of the cross-sections for $e^+e^- \rightarrow \mu^+e^- + 2\tilde{\chi}_1^0$ and $e^+e^- \rightarrow \tau^+\mu^- + 2\tilde{\chi}_1^0$. In this case, the μe channel is enhanced by both the larger Δm_{12}^2 and the smaller m_0 in the new parameter set, resulting in a cross-section one order of magnitude larger than what was found in [8]. For the $\tau\mu$ final state, on the other hand, the effect of the smaller Δm_{23}^2 is compensated by the enhancement due to the smaller value of m_0 , so that the net effect is negligible. As can be seen, for a sufficiently large Majorana mass M_R the LFV cross-sections can reach several fb. The τe channel is strongly suppressed by the small mixing angle θ_{13} , and therefore more difficult to observe.

The Standard Model background mainly comes from W -pair production, W production via t -channel photon exchange, and τ -pair production. A 10

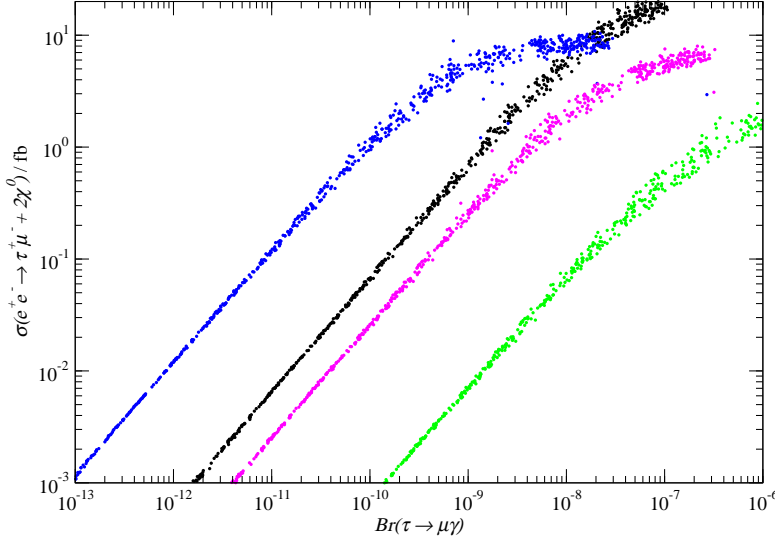


Fig. 7. Correlation between $Br(\tau \rightarrow \mu\gamma)$ and $\sigma(e^+e^- \rightarrow \tau^+\mu^- + 2\tilde{\chi}_1^0)$ at $\sqrt{s} = 800$ GeV for the mSUGRA scenarios (from left to right) C', B', G' and I'.

degree beam pipe cut and cuts on the lepton energy and missing energy reduce the SM background cross-sections to less than 30 fb for μe final states and less than 10 fb for $\tau\mu$ final states. If one requires a signal to background ratio $S/\sqrt{S+B} = 3$, and assumes an integrated luminosity of 1000 fb^{-1} , a signal cross-section of 0.1 fb could only afford a background of about 1 fb. Whether or not such a low background can be achieved by applying selectron selection cuts, for example, on the acoplanarity, lepton polar angle and missing transverse momentum has to be studied in a dedicated simulation. For lepton flavor conserving processes one has found that the SM background to slepton pair production can be reduced to about 2-3 fb at $\sqrt{s} = 500$ GeV [14].

The MSSM background is dominated by chargino/slepton production with a total cross-section of 0.2-5 fb and 2-7 fb for μe and $\tau\mu$ final states, respectively, depending on the SUSY scenario and the collider energy. Here, only the direct processes are accounted for. However, the MSSM background in the τe channel can also contribute to the μe channel via the decay $\tau \rightarrow \mu\nu_\mu\nu_\tau$. If $\tilde{\tau}_1$ and $\tilde{\chi}_1^+$ are very light, like in scenarios B' and I', this background can be as large as 20 fb. On the other hand, such events typically contain two neutrinos in addition to the two LSPs which are also present in the signal events. Thus, after τ decay one has altogether six invisible particles instead of two, which may allow to eliminate also this particularly dangerous MSSM background by cutting on various distributions. But also here this needs to be studied in a careful simulation.

Particularly interesting and useful are the correlations between LFV in radiative decays and slepton pair production. Such a correlation is illustrated in Fig. 6 for $e^+e^- \rightarrow \mu^+e^- + 2\tilde{\chi}_1^0$ and $Br(\mu \rightarrow e\gamma)$. One sees that the neutrino uncertainties drop out, while the sensitivity to the mSUGRA parameters remains. Furthermore, while models C', G' and I' are barely affected by the change in the new parameter set as compared to the set used in [8], in model B' $\sigma(e^+e^- \rightarrow \mu^+e^- + 2\tilde{\chi}_1^0)$ for a given $Br(\mu \rightarrow e\gamma)$ is by a factor 10 larger than in the previous benchmark point B. An observation of $\mu \rightarrow e\gamma$ with a branching ratio smaller than 10^{-11} would thus be compatible with a cross-section as large as 1 fb for $e^+e^- \rightarrow \sum_{b,a} \tilde{l}_b^+ \tilde{l}_a^- \rightarrow \mu^+e^- + 2\tilde{\chi}_1^0$, at least in model C', G' and B'. On the other hand, no signal at the future PSI sensitivity of 10^{-13} would constrain this channel to less than 0.1 fb. The correlation of $Br(\tau \rightarrow \mu\gamma)$ and $\sigma(e^+e^- \rightarrow \tau^+\mu^- + 2\tilde{\chi}_1^0)$ is shown in Fig. 7. $Br(\tau \rightarrow \mu\gamma) < 3 \cdot 10^{-7}$ does not rule out cross-sections in the $\tau\mu$ channel of 1 fb and larger. However, one has to keep in mind that these correlations depend very much on the SUSY scenario.

7 Conclusions

SUSY seesaw models leading to the observed neutrino masses and mixings can be tested by lepton-flavor violating processes involving charged leptons. We have presented an updated analysis of the prospects for radiative rare decays $l_i \rightarrow l_j\gamma$ and slepton pair production and decay $e^+e^- \rightarrow \tilde{l}_b^+ \tilde{l}_a^- \rightarrow l_j^+ l_i^- + \cancel{E}$. Assuming the most recent global fits to neutrino oscillation experiments [10] we have illustrated the impact of the uncertainties in the neutrino parameters. Furthermore, using post-WMAP mSUGRA scenarios [11] we have investigated the dependence of LFV signals on the mSUGRA parameters. For scenario B' our results can be summarized as follows. A measurement of $Br(\mu \rightarrow e\gamma) \approx 10^{-13}$ would probe M_R in the range $5 \cdot 10^{12} \div 5 \cdot 10^{13}$ GeV, while a measurement of $Br(\tau \rightarrow \mu\gamma) \approx 10^{-8}$ would allow to determine $M_R \simeq 10^{15}$ GeV within a factor of 2. Furthermore, $Br(\mu \rightarrow e\gamma) = 10^{-13} \div 10^{-11}$ implies $\sigma(e^+e^- \rightarrow \mu^+e^- + 2\tilde{\chi}_1^0) = 0.02 \div 2$ fb at $\sqrt{s} = 800$ GeV, while $Br(\tau \rightarrow \mu\gamma) = 10^{-8} \div 3 \cdot 10^{-7}$ predicts $\sigma(e^+e^- \rightarrow \tau^+\mu^- + 2\tilde{\chi}_1^0) = 1 \div 10$ fb, again at $\sqrt{s} = 800$ GeV. Hence, linear collider searches are nicely complementary to searches for rare decays at low energies and at the LHC.

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References

1. S. T. Petcov, Sov. J. Nucl. Phys. **25**, 340 (1977) [Yad. Fiz. **25**, 641 (1977) ERRAT,25,698.1977 ERRAT,25,1336.1977]. S. M. Bilenkii, S. T. Petcov and B. Pontecorvo, Phys. Lett. B **67**, 309 (1977).
2. F. Borzumati and A. Masiero, Phys. Rev. Lett. **57**, 961 (1986).
3. J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Rev. D **53**, 2442 (1996) [arXiv:hep-ph/9510309]. R. Barbieri, L. Hall and A. Strumia, Nucl. Phys. B **445**, 219 (1995); G. K. Leontaris and N. D. Tracas, Phys. Lett. B **431**, 90 (1998); W. Buchmuller, D. Delepine and F. Vissani, Phys. Lett. B **459**, 171 (1999); M. E. Gomez, G. K. Leontaris, S. Lola and J. D. Vergados, Phys. Rev. D **59**, 116009 (1999); S. F. King and M. Oliveira, Phys. Rev. D **60**, 035003 (1999); W. Buchmuller, D. Delepine and L. T. Handoko, Nucl. Phys. B **576**, 445 (2000); J. Ellis, M. E. Gomez, G. K. Leontaris, S. Lola and D. V. Nanopoulos, Eur. Phys. J. C **14**, 319 (2000); J. L. Feng, Y. Nir and Y. Shadmi, Phys. Rev. D **61**, 113005 (2000); J. Sato and K. Tobe, Phys. Rev. D **63**, 116010 (2001); D. F. Carvalho, M. E. Gomez and S. Khalil, JHEP **0107**, 001 (2001). J. Sato, K. Tobe and T. Yanagida, Phys. Lett. B **498**, 189 (2001); S. Davidson and A. Ibarra, JHEP **0109**, 013 (2001). P. Ciafaloni, A. Romanino and A. Strumia, Nucl. Phys. B **458**, 3 (1996); J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B **391**, 341 (1997); J. Hisano, D. Nomura, Y. Okada, Y. Shimizu and M. Tanaka, Phys. Rev. D **58**, 116010 (1998); J. Hisano, D. Nomura and T. Yanagida, Phys. Lett. B **437**, 351 (1998); S. W. Baek, N. G. Deshpande, X. G. He and P. Ko, Phys. Rev. D **64**, 055006 (2001); G. Barenboim, K. Huitu and M. Raidal, Phys. Rev. D **63**, 055006 (2001); X. J. Bi and Y. B. Dai; S. Lavignac, I. Masina and C. A. Savoy, Phys. Lett. B **520**, 269 (2001). A. Kageyama, S. Kaneko, N. Shimoyama and M. Tanimoto, Phys. Rev. D **65** 096010 (2002) [arXiv:hep-ph/0112359]; K. S. Babu, B. Dutta and R. N. Mohapatra, Phys. Rev. D **67**, 076006 (2003) [arXiv:hep-ph/0211068]; B. Dutta and R. N. Mohapatra, Phys. Rev. D **68**, 056006 (2003) [arXiv:hep-ph/0305059].
4. J. A. Casas and A. Ibarra, Nucl. Phys. B **618**, 171 (2001) [arXiv:hep-ph/0103065].
5. J. Hisano and D. Nomura, Phys. Rev. D **59**, 116005 (1999) [arXiv:hep-ph/9810479].
6. N. Arkani-Hamed, H. C. Cheng, J. L. Feng and L. J. Hall, Phys. Rev. Lett. **77**, 1937 (1996) [arXiv:hep-ph/9603431]; N. Arkani-Hamed, J. L. Feng, L. J. Hall and H. C. Cheng, Nucl. Phys. B **505**, 3 (1997) [arXiv:hep-ph/9704205]; H. C. Cheng, arXiv:hep-ph/9712427; M. Hirouchi and M. Tanaka, Phys. Rev. D **58**, 032004 (1998) [arXiv:hep-ph/9712532]; J. L. Feng, Int. J. Mod. Phys. A **13**, 2319 (1998) [arXiv:hep-ph/9803319]; J. Hisano, M. M. Nojiri, Y. Shimizu and M. Tanaka, Phys. Rev. D **60**, 055008 (1999) [arXiv:hep-ph/9808410]; D. Nomura, Phys. Rev. D **64**, 075001 (2001) [arXiv:hep-ph/0004256]; M. Dine, Y. Grossman and S. Thomas, eConf **C010630**, P332 (2001) [Int. J. Mod. Phys. A **18**, 2757 (2003)] [arXiv:hep-ph/0111154]. N. Arkani-Hamed, J. L. Feng, L. J. Hall and H. Cheng, Nucl. Phys. B **505** (1997) 3 [hep-ph/9704205]. J. Hisano, M. M. Nojiri, Y. Shimizu and M. Tanaka, Phys. Rev. D **60** (1999) 055008 [hep-ph/9808410]. M. Guchait, J. Kalinowski and P. Roy, Eur. Phys. J. C **21** (2001) 163 [arXiv:hep-ph/0103161]. Phys. Rev. D **66** (2002) 015003 [arXiv:hep-ph/0201284]. Acta Phys. Polon. B **32** (2001) 3755. Acta

- Phys. Polon. B **33** (2002) 2613 [arXiv:hep-ph/0207051]. J. J. Cao, T. Han, X. Zhang and G. R. Lu, Phys. Rev. D **59**, 095001 (1999) [arXiv:hep-ph/9808466]. J. Cao, Z. Xiong and J. M. Yang, Eur. Phys. J. C **32**, 245 (2004) [arXiv:hep-ph/0307126]. M. Cannoni, S. Kolb and O. Panella, Phys. Rev. D **68**, 096002 (2003) [arXiv:hep-ph/0306170].
7. F. Deppisch, H. Päs, A. Redelbach, R. Rückl and Y. Shimizu, Eur. Phys. J. C **28**, 365 (2003) [arXiv:hep-ph/0206122].
 8. F. Deppisch, H. Päs, A. Redelbach, R. Rückl and Y. Shimizu, accepted for publication in Phys. Rev. D, arXiv:hep-ph/0310053.
 9. Homepage Hitoshi Murayama, <http://hitoshi.berkeley.edu/neutrino/>.
 10. M. Maltoni, T. Schwetz, M. A. Tortola and J. W. F. Valle, Phys. Rev. D **68**, 113010 (2003) [arXiv:hep-ph/0309130].
 11. M. Battaglia, A. De Roeck, J. R. Ellis, F. Gianotti, K. A. Olive and L. Pape, arXiv:hep-ph/0306219.
 12. M. Battaglia *et al.*, Eur. Phys. J. C **22** (2001) 535 [arXiv:hep-ph/0106204].
 13. L. Serin and R. Stroynowski, ATLAS Internal Note (1997); T. Ohshima, talk at the 3rd Workshop on Neutrino Oscillations and their Origin (NOON2001), 2001, ICRR, Univ. of Tokyo, Kashiwa, Japan; D. Denegri, private communication.
 14. R. Becker and C. Vander Velde, IIHE-93-08 *Prepared for Working Group on e^+e^- Collisions at 500-GeV: The Physics Potential, Munich, Germany, 20 Nov 1992*.